Technical Report No. 626

CONSTRUCTING SCIENTIFIC EXPLANATIONS FROM TEXT: A THEORY WITH IMPLICATIONS FOR CONCEPTUAL CHANGE

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University of Illinois at Urbana-Champaign

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Center for the Study of Reading

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Abstract

This report outlines Explanation Construction Theory, a psychological theory of how people come to comprehend scientific explanations. Explanation Construction Theory has three components: (a) a theory of how scientific knowledge is represented in memory, (b) a taxonomy of different representations that can be formed in response to an encounter with a text presenting a theory, and (c) a set of factors that influence which of these representations will be constructed.

Constructing Scientific Explanations from Text: A Theory with Implications for Conceptual Change

The purpose of this report is to outline Explanation Construction Theory, a psychological theory of how people come to comprehend scientific explanations. Explanation Construction Theory offers an account of how people construct an understanding of a scientific explanation when they encounter a text that presents the explanation. The text may be written or oral, and it may include illustrations.

At present, Explanation Construction Theory should be regarded as a theory in progress. Empirical tests of many key components are currently being conducted, and the empirical data will undoubtedly point to changes in the theory.

In its current form, Explanation Construction Theory has been developed to account for causal events. A causal event is an episode involving a change with a definable beginning and end. Examples of causal events include a meteor impact producing a mass extinction, a rock breaking a window, and sunlight causing a plant to grow. In each of these events, there is a beginning state (e.g., a meteor hurtling through space toward the earth), an ending state (a devastated planet with numerous species extinct), and a process that mediates the two (the meteor impact produces acid rain, extreme cold, and fires that kill off many species).

In addition to knowledge about causal events, scientific knowledge includes knowledge about static and dynamic equilibria (Chi, de Leeuw, Chiu, & La Vancher, 1994; Iwasaki & Simon, 1994). In the future, I plan to extend the theory to static and dynamic equilibria. This report, however, is concerned only with knowledge about causal events.

Explanation Construction Theory has three components: (a) a theory of how scientific knowledge is represented in memory, (b) a taxonomy of different representations that can be formed in response to an encounter with a text presenting a theory, and (c) a set of factors that influence which of these representations will be constructed. In this report, I will outline each of these components, and I will illustrate the three components by presenting examples from the domain of chemistry. I conclude by discussing some instructional implications of Explnation Construction Theory.

Representations of Scientific Knowledge

In Chinn (1994), I have proposed that scientific knowledge is represented in memory as sets of interlinked explanatory models. The proposed representation owes most to Forbus's (1984) qualitative process theory, Rajamoney & Koo's (1990) extension of qualitative process theory to microscopic models, Johnson-Laird's (1983) mental models, and the notion that mental models can be run as simulations (Gentner & Stevens, 1983).

An explanatory model of a causal event in Explanation Construction Theory consists of a pair of linked mental models. One mental model in the pair is the theoretical model with theoretical entities that cannot be directly observed, such as atoms, electrons, photons, energy, and fields. The second mental model is the data model, which is a model of observable phenomena, such as the disappearance of water set out in a pan or the fire and hotness resulting from lighting a candle. The two models are connected with correspondence rules that specify the relations between the two models.

The theoretical model and the data model are mental models containing entities situated in an imaginistic mental space (e.g., gas molecules far apart from each other flying about in space). However, much of the key information contained in the models is propositional and impossible to represent imaginistically (e.g., energy is conserved; there is nothing, rather than invisible air or ether, between the molecules). The propositional information is combined with the entities so that a person can run the mental model as a simulation (e.g., in a model of evaporation, the faster moving water molecules at the surface escape into the air).

Table 1 presents a detailed example of an explanatory model of evaporation. The model indicates an intermediate level of understanding of evaporation. The model is presented in purely verbal form, with the imagery-based elements redescribed verbally. The actual mental representation would place the entities (bowls of water, molecules moving in space) in spatial arrangements.

[Insert Table 1 about here.]

Data Models, Theoretical Models, and Correspondences

Data Models

Models of phenomena are models of observables; they are the data to be explained by the explanatory model. For evaporation, the macroscopic model describes the water and how it changes, as observed by the naked eye together with simple instruments such as thermometers.

Theoretical Models

Theoretical models explain the macroscopic phenomena by specifying mechanisms with unobservable entities. The theoretical model for evaporation employs atoms and molecules as entities. There are properties and changes involving individual molecules (e.g., escape into the air), and there are properties and changes involving aggregations of the molecules (e.g., heat energy as the sum of the kinetic energy of each individual molecule).

Correspondences Between the Models

A very important part of an explanation is the set of correspondence rules that link the explanatory model with the data model. The links are often nonintuitive. There is, for example, no obvious intuitive reason why temperature in a macroscopic model should correspond to average kinetic energy of molecules in the microscopic model. Indeed, many secondar school students believe that increasing temperature corresponds to individual molecules becoming hotter (Driver, Squires, Rushworth, & Wood-Robinson, 1994) or to a fluid heat flowing in between the molecules (Erickson, 1980).

Components of Theoretical Models and Data Models

A complete theoretical model or data model includes specification of the following: beginning entities with their properties, final entities and properties, the transformations that occur from the beginning to final states, a specification of the constraints on the process, and causal variables. Examples of these components for evaporation are shown in Table 1.

Beginning and Final Entities and Properties

Theoretical models specify theoretical entities and their properties in the initial and final states. Data models specify observable entities and their properties in the initial and final states.

In both theoretical and data models, the initial and final states consist of a set of entities placed in the desired spatial arrangement. Each model specifies relevant properties of the entities; at least some of the properties are implicated in the changes that occur. The initial and final states need not be static states. For instance, water molecules and gaseous molecules are in a dynamic equilibrium involving constant motion and constant movement back and forth across the state boundaries.

Transformations

The models at both the theoretical level and the data level clearly specify the changes that occur from the beginning to the final state. The data model specifies *what* changes occur without specifying how the changes occur. The theoretical model specifies step by step how the changes occur in terms of the theoretical entities.

Constraints

The theoretical model and data model each specify constraints that apply to the transformation. For instance, in the model of evaporation, one constraint that applies to both the theoretical level and the data level is the conservation of mass: The total mass of all entities in the system must remain constant. Some additional constraints that operate at the theoretical level in all chemical reactions are (a) individual atoms never change their mass and (b) individual atoms are neither created nor destroyed.

Causal Variables

Theoretical models and data models also indicate what variables play a causal role in the changes. There are two kinds of causal variables: causal variables internal to a model and causal variables revealed by contrastive models.

Explanation Construction Theory assumes that learners learn that a variable is causal by noticing a contrast (cf. van Fraasen, 1980). For instance, a learner learns that temperature is causally related to evaporation in the phenomenon model by inspecting the contrast between evaporation at a high temperature and evaporation at a low temperature.

Some contrasts occur within a single model (cf. Cheng, 1993). For instance, in the explanatory model of evaporation, it is only the fast-moving molecules moving upward at the surface of the water that escape to the air. The model contains fast-moving and slow-moving molecules, molecules at the surface and molecules below the surface, and molecules traveling in a variety of directions. Explanation Construction Theory postulates that the learner learns the causal effect of speed, location, and direction by contrasting the molecules that escape (fast-moving molecules moving upward at the surface) with several different types of molecules that do not escape (slow-moving molecules, molecules below the surface, and molecules moving sideways or downwards). These contrasts all exist within the single theoretical model.

Other causal factors, however, are not revealed within this single explanatory model. Instead, learners must contrast two models across which one of these factors varies. For instance, the bond strength of water is constant within the explanatory model shown in Table 1. For a learner to notice the role of bond strength in evaporation rate, the learner must contrast this model of evaporation with a model of a substance with a stronger or weaker bond strength, such as isopropyl (rubbing alcohol). Isopropyl has much weaker intermolecular bonds so that the molecules escape to the air occurs much more quickly. By contrasting the explanatory model of isopropyl with the explanatory model of water, the learner apprehends the causal role of bond strength.

Instances

An explanatory model of evaporation either lists instances to which evaporation applies or links different models of evaporation as instances of evaporation. Successful learners may use additional instances of an explanation in two ways. First, by comparing the current instance to an earlier instance, the learner may generalize those features that are common to the two instances (Ross & Spalding, 1991), such as the presence of molecules. Second, the comparison also allows the learner to identify factors, such as what the container is made of or whether the water is flowing, that are not causally relevant. In many models of learning, such as models of concept acquisition, irrelevant features are dropped from abstract, generalized representations. Explanation Construction Theory, however, hypothesizes that some irrelevant factors may be remembered and generalized to other processes, such as boiling or reactions.

Connections with Contrastive Cases

Experts may encode external causal contrasts such as bond strength as abstract variables within a single abstract model for evaporation; this is the approach used in Table 1. Novices, however, may need to begin by constructing separate representations for evaporation with weak bonds and evaporation with strong bonds and then linking these models in memory to show the causal role of bond strength. If so, then making connections with contrastive models should be crucial to learning all the factors that can influence a process such as evaporation.

Theories and Recurrent Model Components

According to Explanation Construction Theory, knowing a scientific theory means knowing a set of interrelated models (cf. Giere, 1988). For instance, knowing molecular theory means knowing molecular models for evaporation, melting, freezing, condensation, combustion reactions, endothermic solution reactions, exothermic solutions reactions, elastic repulsion, and many other processes. All of these models are united by a set of common underlying entities, common properties of entities, common processes, common constraints on processes, and correspondence rules that recur in numerous models. For example, the microscopic model of a liquid, with molecules moving past each other, constantly making and breaking weak intermolecular bonds, recurs in any model involving liquids. The correspondence rule linking temperature and average kinetic energy of molecules recurs in evaporation, melting, reactions of all sorts, friction, and many other models. The constraint that energy must be conserved recurs in every process. Processes such as bond-breaking, bond formation, and temperature increase through friction appear over and over. It is all of these recurring components of explanatory models that unify a theory. To learn a theory is to learn these recurring components and how they fit together in numerous models.

Representations Formed upon Encountering a New Explanatory Model

The second component of Explanation Construction Theory is a taxonomy of representations that people may construct when they encounter scientific theories that contradict their current ideas. Notice that constructing a representation for a theory does not entail believing that theory; a person can, for instance, construct a representation of the geocentric model of the solar system without believing it. According to Explanation Construction Theory, a person can construct any of four types of representation upon encountering a model that contradicts current beliefs: (a) the learner constructs no new representations, (b) the learner constructs a rote representation, (c) the learner updates the current model but does not construct a separate representation for the new model, and (d) the learner constructs an alternative representation for the new model.

Constructing No Representation

Sometimes learners make no attempt to construct any new representation of the theory. Instead, the learners ignore the new theory or use particular words within the model as cues that remind them of information irrelevant to the theory (Roth & Anderson, 1988). In neither case is a new model constructed.

Constructing a Rote Representation

Learners may construct a rote representation of a scientific theory without understanding any of it. A rote representation is a representation that preserves superficial linguistic structures or pictorial elements but has no underlying meaning (see Brewer & Pani, 1983).

Updating the Current Model

Learners who update their current models do not attempt to understand the contradictory model as a model distinct from their own system of models. Instead, they take bits and pieces from the new model in order to update their old models. These learners process a text (oral or written) piece by piece, perhaps sentence by sentence or paragraph by paragraph. The learners do construct separate representations for each new piece of information, but the representation of each piece is fragmentary and is not integrated with the other pieces in a single coherent representation of the new model. Learners compare each piece of new information presented in the text with their old beliefs. Then the learners may choose to alter the old beliefs before going on to the next piece of new information. Thus, although the learner reads each piece of information, the learner makes no attempt to construct a complete, integrated representation of the alternative model.

As the learner processes each piece of information, he or she may take any of these actions: (a) The learner may *reject* the new information as incorrect and maintain the old belief system without any change. (b) The learner may *assimilate* the new information by (mistakenly) interpreting the new information as being identical to information already present in the old belief system. (c) If the learner cannot understand the new information, the learner may *discard* it *as incomprehensible* and think about it no further. (d) The new information may lead the learner to *modify* the old belief system.

Constructing an Alternative Model

An individual's most sophisticated response upon encountering a new explanatory model (or set of explanatory models) that contradicts old beliefs is to try to construct a distinct, separate representation of the explanatory model. The individual attempts to keep the current model separate from the representation of the new model. Then the two models can be compared and evaluated in toto.

An alternative representation differs from an updated representation in three crucial respects:

(a) The learner suspends belief.

(b) The learner constructs the representation using shared building-block concepts.

(c) The learner leaves gaps where understanding is incomplete.

Suspending belief. To construct an alternative model, learners must separate belief from understanding. An alternative theory may not be believable until the learner has had a chance to construct numerous explanatory models and see how the explanatory models explain a range of data. When belief is segregated from understanding, the learner is freer to incorporate elements into the new explanatory models that may at first seem absurd.

Use of shared building-block concepts. It is widely accepted that new ideas are comprehended by integrating them with prior knowledge (e.g., Anderson & Pearson, 1984). But how could a learner ever come to understand a new theory that is fundamentally different from an old theory? How could concepts from the old theory be used to comprehend a new theory with incompatible concepts? The answer, according to Explanation Construction Theory, is that models in the new theory are often not constructed from elements of the old theory; rather, models in the new theory are constructed from elements of knowledge that are common to both the old and new theories or from elements of knowledge that play no role in the old theory.

As an illustration, consider a student who encounters a description of the molecular model of matter for the first time. The student's prior model of matter posits that matter is continuous and homogeneous. Then the student reads an account of the molecular theory, including the ideas that matter is constructed of tiny balls called molecules and that there is empty space between the molecules. The concepts *tiny balls* and *empty space* are *building-block concepts* that play no role at all in the old theory that matter is continuous. As long as students understand these concepts, they should be able to construct an alternative representation that is independent of the original theory. The accuracy of the representation depends on whether the text author and the reader share the same building-block concepts, not on whether they share the same theory. If the reader conceptualizes balls as footballs and empty space as always having some air in it, the reader's representation will be very different from the author's representation, but it will also be very different from the initial homogeneous model. Thus, new theories can be constructed from lower level, building-block concepts that either are not specifically part of the old theory or are shared by both the old and new theories.

Gaps where knowledge is incomplete. Because a new alternative model may be complex, learners may find it nearly impossible to build up a complete model without a series of increasingly deep encounters with models in the theory. As the learner tries to understand new, contradictory model, there will be a need to leave gaps in the representation. For instance, the learner learning about evaporation may be unclear about where the escaped molecules go. The alternative representation will probably be corrupted if the learner wantonly imports prior knowledge to fill such gaps.

Obstacles to Constructing an Alternative Model

When a learner attempts to construct a representation for an alternative theory from a text, the constructed representation often differs from the writer's intended representation. Explanation Construction Theory assumes that writers who describe a theory intend the reader to acquire an understanding of that theory that is shared with the writer. Failures by the reader to understand what the writer intended could be revealed in a conversation between the reader and the writer, in which the conversants made repair moves such as "No, that's not what I was trying to say," "Actually, the molecules are moving all the time," or "So you mean that there is a vacuum between the molecules?" When no such repair moves occur, we may assume that the reader and writer hold identical representations of the theory.

Explanation Construction Theory postulates three general types of discrepancy between the reader's representation and the writer's representation: omissions, importations, and distortions. To illustrate, I will refer to the explanation of evaporation shown in Table 1.

Omissions of single explanation components. A omission occurs when the reader's representation of a model lacks components found in the writer's representation. For instance, secondary school chemistry students often fail to include "moving" as a property of molecules in solids, and they often fail to encode the conservation of molecules as a constraint on interactions. They may also omit from their model the correspondence between water vapor and humidity. Some students may omit the entire data model, never realizing what it is that the microscopic model is supposed to explain!

One particularly important omission is the omission of a mechanism, as when a learner knows that molecules leave the water during evaporation but does not understand why this occurs. A related omission occurs when learners encode external causal factors but do not recognize how outcomes vary with those factors. For instance, learners may realize that bond strength has to be overcome during evaporation but not that bond strength may vary, so that evaporation occurs more rapidly when the bond strength is low.

Learners may construct a representation of a explanatory model but fail to construct additional explanatory models to which that core explanatory model can be linked. There are two main types of explanatory models that can be omitted. First, learners can omit contrastive models, which are hypothesized to be necessary for understanding the role of some causal variables. Second, learners can omit other instances to which the model applies. This can result in undergeneralization of the model.

Importations. Importations are the opposite of omissions: The learner incorporates an inappropriate idea from old knowledge into a model. That is, the learner imports from old knowledge an idea that does not exist in the writer's model. Any model component can be imported. For instance, secondary school learners often assume that molecules in cold water have the property of being wet and being cold, just as macroscopic water does. These learners have imported the macroscopic properties of water into the theoretical model. Similarly, learners may interpret the "empty space" between molecules to be air. Mechanisms may also be imported, as when a learner who reads a text giving a sketchy, incomplete account of evaporation assumes that the mechanism for evaporation must be that the molecules disappear, or that some water molecules are lighter than others so that they belong in the air.

Chi (1992) has argued that learning science is especially difficult when the learner's concepts belong to a different ontological category from the writer. For example, novices view concepts such as heat and energy are material substances, whereas scientists view heat and energy as a relations among material substances. In the view of Explanation Construction Theory, this leads novices to import material properties that do not belong in the scientists' model.

Sometimes learners may import linked explanations that should not be linked to an explanation. One common importation of this sort is the importation of explanations to which the explanatory model should not apply, such as assuming that the mechanism that produces evaporation (escape of surface molecules) applies to boiling water, as well.

Inappropriate linked instances can also be imported, as when a student connects state change processes such as boiling as instances of models of chemical reactions. Importing inappropriate instances means that the explanatory model is overgeneralized.

Tagged and Untagged Omissions and Importations. Explanation Construction Theory makes a distinction between tagged omissions and importations and untagged omissions and importations. An untagged omission is one that the reader is unaware of; a tagged omission is one that readers consciously mark as being a gap their knowledge. An untagged importation is one that the learner makes without realizing it; a tagged importation occurs when the reader consciously decides to make an assumption, while realizing that the assumption may be unwarranted. Tagged omissions and importations may be easier to repair than untagged omissions, because the learner may set and maintain a goal of finding new information to fill the tagged gap or to check on the tagged importation.

Distortions. Learners can also distort information that they encounter. For instance, students may read that water molecules behave as if they were hard and yet continue to believe that water molecules are soft. This is not a problem of omitting information or importing information. The information in the text is overridden. It is either ignored or changed, probably because it does not make sense to the learner.

Factors that Influence Which Representation Will Be Constructed

The third component of Explanation Construction Theory is a specification of factors that are hypothesized to influence the construction of representations of new theories that contradict old beliefs. The theory postulates four classes of factors that can influence which representation is constructed: (a) the learner's goals and interests, (b) the learner's beliefs about the nature and structure of scientific knowledge, (c) the learner's naive beliefs about learning science, and (d) the fit between the information presented in the texts and the learner's prior knowledge.

Goals and Interests

Learners will construct a representation only if they have set themselves the goal of constructing a representation. To construct complete alternative models, learners must set themselves the goal of understanding how the new theory accounts for a variety of data. A useful way of promoting this goal is to have students explain many phenomena; their interest should be further whetted if many of the phenomena are drawn from everyday life.

If the learner's initial theory is highly entrenched (see Chinn & Brewer, 1993), the learner may feel that it is not worth the trouble to learn a new theory that is obviously wrong. Thus, an entrenched initial theory may be a strong impediment to motivation.

The Learner's Beliefs about the Nature and Structure of Scientific Knowledge

A learner's beliefs about the nature and structure of scientific knowledge may affect learning. For instance, students who do not fully understand the distinction between data models and theoretical models will probably have difficulty learning scientific explanations (Kuhn, 1989). Students who do not understand that rival theories may exist and that these theories compete to try to explain a given body of data may fail to understand the need to keep new explanatory models distinct from old beliefs. Students who think that science is an accumulation of observable facts and vocabulary may have difficulty constructing scientific explanations (cf. Songer & Linn, 1991). Students who do believe that new scientific information must be consistent with what they already know may commit numerous importations and distortions.

The Learner's Naive Theories of Learning

Learners possess many beliefs about learning that could affect their ability to construct an accurate alternative model. Explanation Construction Theory hypothesizes that two beliefs may be particularly beneficial. The first is the belief that active explanation promotes understanding. The learner who does not actively strive to construct explanations may be particularly prone to omissions. The second important belief is the realization that one cannot learn a scientific model all at once; instead, it is necessary to leave gaps or sometimes make guesses until a time when additional information is given. Learners who tag their gaps and importations may be more likely to fill gaps and correct incorrect importations later on (cf. Chan, Burtis, Scardamalia, & Bereiter, 1992).

The Fit Between the Information Presented in the Texts and the Learner's Prior Knowledge

Mismatches between the information presented in the text and the learner's prior knowledge can cause omissions and importations to proliferate. One type of mismatch occurs, as many researchers have noted, when writers and readers assign qualitatively different meanings to terms. For the scientist, heat and energy are unsubstantial properties of matter; for the student, heat and energy may be fluid-like substances with weight. For the scientist, air consists of molecules with a vacuum between them; for the student, air may be a homogenous substance with no mass. Obviously, in such situations, writers cannot use the terms *heat*, *energy*, or *air* without considerable explanation. Sentences such as "Heat flows from the warm water to the cold water" can only reinforce the child's misconception. The difficulties are not limited to technical terms; a text stating that water molecules "escape" into the atmosphere may lead learners to think that the atmosphere is the natural home to which water molecules want to return. Similarly, the phrase "the molecules in the water" may suggest to the child that water consists of generic molecules surrounded by models like raisins in a pudding.

There are at least two possible remedies to such difficulties with language usage. One is to avoid using technical terms such as *heat* and *energy* and instead to retreat to a more theory-neutral vocabulary, at least for a while. Nontechnical terms that are misleading should be avoided altogether, and technical terms could be reintroduced later. A second remedy is to explain carefully how the scientific meaning differs from the learner's meaning. Although these approaches seem plausible, neither has been, to my knowledge, tested experimentally.

Another type of text-reader mismatch occurs when texts are sketchy with respect to the reader's knowledge. Science textbooks typically present only a few of the numerous components of explanatory models. Such texts guarantee omissions, as learners simply cannot guess what goes in the gaps or do not realize that there are any gaps. At the same time, these texts encourage importations, as learners must import ideas to make even minimal sense of the text. For instance, a text that merely states "Evaporation occurs when the molecules in the water go up into the air" specifies no mechanism, leaving learners free to assign their own mechanisms. The obvious remedy is to make texts more explicit. For instance, a text explaining evaporation should clearly specify all of the components listed in Table 1; if the learner does not have a firm understanding of the microscopic models of liquids and gases, these should also be clearly specified.

Undesired importations can be blocked in either of two ways: by using concepts inconsistent with that importation or by explicitly stating that the importation is unwarranted. For instance, students often import the property of wetness to describe individual molecules. To block this importation, the writer could assert that individual molecules are "hard and dry," which would be inconsistent with the property of wetness, or the writer could directly assert that individual molecules are not wet. These are instances of *specific refutations*, which are aimed at blocking specific importations that students may make.

A common source of difficulty is students' failure to understand how the correspondence rules could be plausible. It seems implausible to young learners that hard molecules of water could correspond to something smooth, wet, and pourable. One solution is to provide additional information that can make this plausible. One could point out that whereas a bowl of marbles consists of hard particles that feel hard as a group, a bowl of canary seed consists of tiny spheres which, although hard and unpourable individually, feel smooth and can be stirred and poured as a group. This additional information could make it plausible that even smaller molecules could end up producing the properties possessed by water.

Most textbooks, and indeed most researchers who do research on explanatory models (e.g., Mayer, 1989), use single models in their instructional interventions. However, Explanation Construction Theory insists that novices cannot learn about the full range of causal factors without inspecting contrasting models. To understand how the presence of a solute affects evaporation, the learner must contrast a model of evaporation with a solute with a model of evaporation without a solute. Therefore, writers should present multiple, contrastive models.

In a similar way, text authors can preclude omission of instances by specifying these instances. For instance, writers could point out that the evaporation model applies not only to drops of water on a kitchen pan but also puddles of water outside, ponds and lakes, the ocean, drops of gasoline spilled at a gas station, rubbing alcohol rubbed on the skin, sweat on the skin, and so on. The function of these additional instances is the opposite of contrastive instances. These instances show what aspects of the current model are irrelevant, instead of which are causally relevant. Science educators frequently encourage the use of everyday examples to make sure that students learn to apply scientific theories to everyday life; the effectiveness of this highly plausible notion has not been systematically tested.

For students to remedy incorrect importations and fill in omissions, it is necessary to revisit those explanations. Obviously, if a student constructs a faulty explanatory model and then never has occasion to think about that particular model again, the student will have no opportunity to improve the model. Therefore, it seems essential that students revisit explanatory models that they constructed previously so that they can work on them, revising and refining them.

Instructional Implications of Explanation Construction Theory

The preceding analysis points to several instructional procedures that could help students learn new theories that contradict their own theories.

One procedure is to encourage active reflection and explanation using the descriptions of models found in texts. If students actively reflect on the theory and use the theory to explain phenomena, they should eventually be able to achieve a model that approximates the model intended by the writer of the text. Generating explanations in addition to reading them should prevent omissions due to lazy processing. This recommendation follows that of researchers who have investigated the beneficial effects of explaining material to oneself as one studies (e.g., Bielaczyc, Pirolli, & Brown, 1994; Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi et al., 1994).

A second procedure is to revisit previously constructed alternative explanations after acquiring new knowledge to see if the new knowledge suggests any changes to those old explanations. It is essential to have multiple opportunities to construct accurate representations of complex explanatory models.

A third procedure is to work with students to try to change their beliefs about the nature of science and their beliefs about learning science. If students become aware that science is not an enterprise of accumulating facts but rather an endeavor to construct explanatory models, which are often complex, then students should be more successful at learning these models.

A fourth procedure is to present students with numerous explanations within a theory, including both contrastive explanations and additional instances. Contrastive explanations should alert students to causal factors that they would otherwise not notice. Additional instances should help students avoid overgeneralizing or undergeneralizing the explanations that they have learned. These assumptions are consistent with Spiro et al.'s (1987) advocacy of the use of multiple cases to promote flexible use of knowledge.

The fifth procedure is to use highly explicit texts. It is possible that the main reason for the difficulty students have in learning scientific models is that they are never given clear presentations of these models! Because fragmentary descriptions of new theories are probably a main cause of omissions and importations, texts that clearly present all components of the model should facilitate construction of accurate models. To be explicit, texts should specify all of the components listed in Table 1. Texts should include the explanatory model, the data model, and the correspondences between the models. If necessary, the correspondences may be supported with information to make them plausible. The model should specify entities, properties, constraints, and internal causal contrasts. When contrastive models are provided, the contrasts should be highlighted. In addition, where necessary, the texts may include specific refutations. There is research showing that refutations are effective at promoting conceptual change (Guzzetti, Snyder, Glass, & Gamas, 1993), but the effectiveness of different types of refutation has not been examined. Explanation Construction Theory proposes that specific refutations that block specific importations should be particularly effective.

Summary and Conclusions

This report has described Explanation Construction Theory, a theory of how people learn scientific theories from oral or written texts. Explanation Construction Theory includes a theory of how scientific knowledge is represented in memory, a taxonomy of the different kinds of representations an individual can construct upon learning about a new theory, and a set of factors that influences what kind of representation is constructed. Explanation Construction Theory makes several recommendations for instruction.

Explanation Construction Theory is currently undergoing a series of empirical tests. One large study is underway to test the claim that explicit texts with multiple contrasts enhance understanding of difficult scientific models. A second group of studies is planned or underway to test Explanation Construction Theory's claims about the kind of information that should be presented in an explicit text. A third line of research investigates the distinction between updating the current model and constructing an alternative model. If the results of these studies provide support for Explanation Construction Theory, a very important claim will emerge: A central reason why students do not understand scientific theories is that they typically do not encounter descriptions of the theories that are sufficiently clear and explicit.

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Table 1

Explanation for Evaporation

CATEGORIES	Macro Level	Correspondences	Micro Level
Beginning Entities, Relations, and Properties	Water is in bowl. Properties of water: --fluid --stirrable --pourable --spreads downward and outward to fill spaces --smooth and wet --holds together unless poured Air surrounds water and bowl. Properties of air: --fluid --airy, wispy to the touch --space-filling --doesn't seem very substantial	Macroscopic water corresponds to the water molecules. There are billions of molecules even in the smallest drop of water one can see. The properties of water and air are properties of all the molecules together, not the properties of individual molecules. (This is analogous to canary seed; each seed is hard and round, but all together, they approach fluidity.) Fluidity of waater derives from the speed of the molecules relative to the intermolecular attractions. Air is "wispier," or less substantial, than water because it has much more open space between molecules and becuse there is no intermolecular attraction between the molecules. Mass of water = sum of masses of liquid water molecules. Mass of air = sum of masses of molecules that make up the air.	Water molecules in bowl, composed of 2 hydrogen (H) atoms and 1 oxygen (O) atom. Properties: --vacuum between molecules --distance between molecules of about one molecular radius. --molecules constantly moving; they constantly slide past and bump into each other --speed of molecules varies around a mean --motion is random in direction --behave as if they were hard --intermolecular attractions between O atom of one molecule and one of the H atoms of an adjacent molecule --molecules move as units Gas molecules all around the water and pan molecules. There are molecules of four gases--nitrogen, oxygen, carbon dioxide, and water vapor. Properties: --vacuum between molecules --distance between molecules of about ten molecular radii --molecules constantly moving; they move freely --speed of molecules varies around a mean --motion is random in direction --behave as if they were hard, perfectly elastic --no intermolecular attractions --molecules move as units

Changes	Water level steadily decreases until the water disappears. Humidity in air increases. Temperatures of water decreases slightly.	Decrease in water level corresponds to movement of water molecules from liquid to gas. Increase in humidity corresponds to increase in number of water molecules in the air. Decrease in temperature corresponds to decrease in average speed of water molecules and air molecules.	Liquid water molecules escape from the surface of water and diffuse among molecules in the air. Number of water molecules in liquid decreases as number of water molecules in air increases. Kinetic energy of the molecules is converted to potential chemical energy. Because the fastest molecules at the surface of the water escape, the molecules left behind are, on the average, slower.
Constraints	Total mass remains constant.		Number of molecules and atoms remains constant. Number of water molecules and air molecules remains constant. No molecule changes internal structure or individual properties. Total energy is constant.
Final Entities, Relations, & Properties	There is no water in the bowl. The humidity of the air is higher. The temperature of the air is lower.	See above	Same as beginning state, except: --There are more water molecules in the air. --There are no water molecules in the bowl. --All air molecules are moving slightly slower than before.
Causal variables internal to the model	Presence of water		If water molecules are moving upward and outward at a critical velocity, then the molecules escape and become water vapor molecules. Why: speed overcomes bond strength. If water molecules are moving sideways or downward at any velocity, then they remain in the liquid water. Why? Nowhere to escape. If water molecules move upward and outward at the surface of the liquid at a slow speed, then they do not escape from the surface. Why? The intermolecular bonds hold them. As molecules escape from the intermolecular bonds, they slow down because of the drag of the bonds as they are leaving.

Table 1 (Continued)

Causal variables revealed by contrastive models:	Higher temperature increases the rate of evaporation.	Higher temperature corresponds to greater speed of molecules	The molecules have a higher average speed. This means that there are also a larger number of molecules with speed great enough to escape the molecular bonds, so more molecules escape.
	Different substances evaporate at different rates.	Different substances are composed of different molecules. The faster evaporation occurs with molecules with weaker intermolecular attraction; more molecules leaving the liquid means faster evaporation.	Different substances have different intermolecular attractions. When intermolecular attractions are weak, it doesn't take much speed to overcome the force of the attraction, so many molecules leave the surface of the water.
	Increased surface area increases the rate of evaporation.	Greater surface areas have more molecules on the surface.	When more molecules are exposed to the air, it is more likely that fast-moving molecules will be at the surface; therefore, more molecules will leave the ater and go up into the air.
	Increased humidity decreases the rate of evaporation.	Greater humidity corresponds to a greater concentration of water vapor in the air. Greater number of collisions of water vapor molecules with the water corresponds to more vapor molecules becoming attached to the liquid water molecules. More water molecules attached to the liquid molecules means a greater rate of condensation and thus a lower net rate of evaporation.	With a greater number of water molecules in the air, there is an increased likelihood of a collision with other vapor molecules or with water molecules at the surface. When slower-moving water molecules that are part of the air collide with water molecules that are part of the liquid, then they stick together.
	Presence of solutes in the liquid slows the rate of evaporation.	Dissolved substances correspond to molecules of the dissolved substance surrounded by liquid molecules. The decreased rate of evaporation corresponds to fewer molecules leaving the water.	The molecules of the solute take up space at the surface of the liquid, which means that there is a smaller number of molecules that can leave the water. The solute molecules are also strongly attracted to the liquid molecules, so that it takes a much greater speed to overcome the attraction. Fewer liquid molecules have this great speed, so there are fewer molecules that go into the air.